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Three-dimensional semi-idealized model for estuarine turbidity maxima in tidally dominated estuaries

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A B S T R A C T

We develop a three-dimensional idealized model that is specifically aimed at gaining insight in the physical mechanisms resulting in the formation of estuarine turbidity maxima in tidally dominated estuaries. First, the three-dimensional equations for water motion and suspended sediment concentration together with the so-called morphodynamic equilibrium condition, are scaled. Next, surface elevation, velocity and sediment concentration are expanded in a small parameter $\epsilon = \bar{A}_{M_2}/H$, where $\bar{A}_{M_2}$ is the mean amplitude of the M_2 tide and H is the mean water depth at the seaward side. This results in a system of equations at each order in this small parameter. This ordering allows solving for the vertical structure of the velocity and suspended sediment concentration, independently of the horizontal dimension. After obtaining these vertical structures, the horizontal dependencies of the physical variables follow from solving a two-dimensional elliptic partial differential equation for the surface elevation. The availability of fine sediments in the estuary follows from a two-dimensional elliptic partial differential equation which results from requiring the system to be in morphodynamic equilibrium, and prescribing the total amount of easily erodible sediments available in the estuary. These elliptic equations for the surface elevation and sediment availability are solved numerically using the finite element method with cubic polynomials as basis functions. As a first application, the model is applied to the Ems estuary using a simplified geometry and bathymetric profiles characteristic for the years 1980 and 2005. The availability of fine sediments and location of maximum concentration are investigated for different lateral depth profiles. In the first experiment, a uniform lateral depth is considered. In this case, both the sediment availability and suspended sediment concentration are, as expected, uniform in the lateral direction. In 1980, the sediment is mainly trapped near the entrance, while in 2005, the sediment is mostly trapped in the freshwater zone. In the next experiment, the lateral bathymetry is varied parabolically while keeping the mean depth unchanged. In this case, the fine sediment is mainly found at the shallow sides, but the maximum sediment concentration is found in the deeper channel where the bed shear stress is much larger than on the shoals. As a final experiment, a more realistic (but smoothed) geometry and bathymetry for the Ems estuary are considered, showing the possibilities of applying the newly developed model to complex geometries and bathymetries.

1. Introduction

In most estuaries, regions are observed with elevated suspended sediment concentration compared with the adjacent landward and seaward regions. These regions are called *estuarine turbidity maxima* (ETM). A good understanding of the ETM dynamics is important for many reasons (for a detailed discussion, see Jay et al., 2015). First, the presence of an ETM can have a strong influence on the ecological functioning of an estuary, as it can result in limited light conditions or anoxia (Talke et al., 2009b). Furthermore, at the location of the ETM, there is often a considerable deposition of fine sediments, which results in enhanced dredging

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efforts to keep the estuary accessible and the navigation lanes at their regular depths. Finally, ETM dynamics is shown to be sensitive to changes in bathymetry, geometry and external forcing conditions (de Jonge et al., 2014), which (if not well understood) can result in a deterioration of the system as a whole.

To better understand and assess the effects of natural or anthropogenic changes on ETM dynamics, different types of models are being applied (Murray, 2003). For example, state-of-the-art three dimensional process-based models are applied to simulate ETM dynamics (Weilbeer, 2008; van Maren et al., 2015) and changes in ETM dynamics due to human interventions. However, these models are computationally expensive and the mechanisms resulting in the observed dynamics are difficult to analyse (Schuttelaars et al., 2013).

Alternatively, process-based idealized models are specifically designed to and aimed towards studying the mechanisms resulting in the formation of ETMs and assessing their sensitivity to parameters. Since these models focus on a specific phenomenon, some processes are not or only parametrically taken into account. Furthermore, geometry and bathymetry are often simplified. Huijts et al. (2006) used an idealized modelling approach to study the trapping of fine sediments in the lateral direction. Talke et al. (2009a) and Chernetsky et al. (2010) focused on the sediment transport in the longitudinal direction, using a width-averaged model. However, Geyer et al. (1998) and Kim and Voulgaris (2008) pointed out that the lateral water motion and suspended sediment dynamics affect the processes in the longitudinal direction and vice-versa. Therefore, to understand the ETM dynamics and the underlying dominant trapping mechanisms (see for example Jay et al., 2015 for an overview of possible mechanisms), it is necessary to study both the lateral and longitudinal processes simultaneously. Clearly, this requires a three-dimensional modelling approach.

For the water motion, three-dimensional idealized models have been developed and analysed in detail (Winant, 2007; 2008; Ensing et al., 2015; Kumar et al., 2016), but for the sediment transport and trapping of fine sediments, three-dimensional idealized models are still missing. Therefore, the aim of this paper is to develop a three-dimensional idealized model for water motion and sediment dynamics in an estuary of arbitrary shape and bathymetry, including the Coriolis effect. This allows for a systematic study of the sediment trapping mechanisms in a tidally-dominated estuaries. The physical parameters are allowed to vary in the horizontal plane. The three-dimensional model is solved using an asymptotic expansion technique. This results in analytic solutions of the vertical profiles of the velocity and suspended sediment concentration. These solutions still depend on the (gradients of the) surface elevation. The surface elevation itself follows from a two-dimensional elliptic partial differential equation which is solved numerically using the finite element method. The condition of morphodynamic equilibrium is prescribed to govern the availability of fine sediments in the estuary.

As a first example, the new model is applied to the Ems estuary using simplified geometric and bathymetric profiles characteristic for 1980 and 2005. The location of maximum trapping of sediments for both years is investigated. The influence of lateral bathymetry is investigated by first keeping the depth in the lateral direction uniform. Next, the lateral bathymetric profile is varied parabolically while keeping the width-averaged depth unchanged. The results are qualitatively compared with observations and the influence of lateral depth variations is discussed. As a final example, we use the (smoothed) observed bathymetry and geometry of the Ems in 2005 to obtain the trapping location of the fine sediments.

The structure of the paper is as follows. The philosophy of idealized modelling and step by step overview of model development are presented in Section 2. The model equations of water motion and suspended sediment concentration and the condition of morphodynamic equilibrium are presented in Section 3. This section also presents the scaling and perturbation analyses which results in a system of equations at each order for the water motion and the suspended sediment concentration. The leading-order system for the water motion is solved in Section 4, the first-order system in Section 5. Similarly, the leading-order and first-order systems for suspended sediment concentrations are solved in Sections 6 and 7, respectively. The equation for sediment availability governing the distribution of fine sediments in the estuary is solved in Section 8. Section 9 gives a short description of the numerical solution procedure for the two-dimensional elliptic partial differential equations obtained for both the surface elevation and sediment availability with a special discussion on the accuracy of the resulting solutions. Next, this model is applied to the Ems estuary in Section 10. Finally, conclusions are presented in section 11.

2. Idealized model - model philosophy

The main research question will be answered by developing a so-called *idealized, process-based model*. Idealized models focus on specific phenomena (here ETM formation), neglecting or simplifying processes that are not essential for the phenomenon under study. In this paper, we focus on developing such a model for a tidally dominated, well-mixed estuary. It is assumed that the suspended sediment concentrations do not influence the water motion significantly, and that the water motion is mainly driven by a prescribed M_2 tide at the seaward side.

In constructing this idealized model, ten steps can be identified. These steps are visualized in Fig. 1; the precise sections where the individual steps are discussed in detail, are indicated in this figure as well. Below, the main steps are summarized:

1. Derive the model equations, and define the geometry and bathymetry of interest.
2. Make the physical variables (such as surface elevation, water depth, etc.) dimensionless by introducing typical scales; subsequently use this to make the governing equations dimensionless. Since all dimensionless physical variables are order one, the relative importance of each term in any of the equations is measured by the magnitude of the dimensionless number, multiplying the dimensionless group of physical variables. These magnitudes can be calculated explicitly after choosing scales that are representative for the estuary/class of estuaries under consideration.
3. Verify that one of the dimensionless numbers is the ratio of the M_2 surface elevation averaged over the entrance (A_{M_2}) and the mean water depth H at the seaward boundary. This ratio, denoted by ϵ, is much smaller than one. Next, all other dimensionless numbers are related to ϵ.
4. Expand the physical variables in the small parameter ϵ. These asymptotic expansions are introduced in the dimensionless equations, and terms of equal order in ϵ are collected. Since only terms of equal order in ϵ can balance, this results in a system of equations at each order in ϵ.
5. Construct the solutions for the leading-order water motion, i.e., at order ϵ^0. Since the leading-order water motion is only driven by the M_2 tidal signal at the seaward boundary, it only consists of an M_2 constituent.
6. Derive the first-order water motion using the leading-order water motion, i.e., ϵ^1. It is found that the temporal variations of the first order water motion consist of a residual and an M_4 contribution.
7. Calculate the leading-order concentration using the leading-order water motion. Concerning its temporal behaviour, a resid-